EFFECTS OF ELECTROKINETIC TREATMENTS ON THE PROPERTIES OF A SALT AFFECTED SOIL

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SUMMARY

This paper presents experimental results of a study undertaken to investigate the effects of electrokinetic treatments on selected chemical and physical properties of a salt contaminated (saline) soil. The study was conducted as a laboratory scale pilot project using locally available saline soil samples. The soil was subjected to an electric gradient by passing a direct current between inserted electrodes. After certain electrokinetic treatment periods, the properties of the soil were evaluated. The experimental data reveals that electrokinetic techniques could offer a low cost, rapid solution to treat saline soils. The removal efficiency of sodium ions was found to be greater than 90% within a relatively short time period of 14 to 30 days, using low current and voltage systems. After 14 to 30 days, the degree of salinity and sodicity decreased to a very low or negligible level. The unconfined compression strength of the soil increased by between 30 % to 100% in 30 days of electrokinetic treatment indicating the improvements in the physical properties, especially in the stress-strain characteristics of the soil. The liquid limit (LL) and plastic limit (PL) increased at the cathode.

1 INTRODUCTION

Salinity continues to be a major form of land degradation and a significant environmental threat in Australia (Salt Force, 1988; NLWRA, 2000; SCARM Report 78, 2000). The adverse impacts of salinity extend over a wide spectrum that includes productive agricultural land, river systems, ecosystems and infrastructure (CSIRO, 2003). Removal of deep-rooted native trees, grasses and vegetation and the consequent intervention in the natural water balance, is considered as the major cause for soil salinisation (CSIRO, Land and water; DNRE, 2002). With large scale clearing of native vegetation (particularly deep rooted perennials and eucalyptus) and their replacement with shallow-rooted agricultural plants (crops and pastures) any water added to the system in excess of evaporation and plant needs will seep through the soil recharging the groundwater causing the water table to rise (McRobert et al., 2003). When the groundwater table rises, it brings an excess amount of salt to the surface that was otherwise stored at deeper depths. The water evaporates leaving the salt in the surface layers of the soil.

Dissolved salts and exchangeable sodium ions in the soil solution and the exchange phase affects soil physical properties such as structural stability, hydraulic conductivity, infiltration rate, runoff and erosion (Shainberg et al., 2001). Other than the direct effects that these soil properties have on plant growth, significant detrimental affects on built infrastructure have been reported (e.g. Geo-Enviro, 2001; McRobert et al., 2003; Water Smart, 2003; Wilson, 2003).

There are many long term strategic approaches and programs initiated to minimise the effects of salinity, particularly on agricultural productivity. Although the salinity threat on infrastructure such as roads, rail, embankments, houses and underground structures is increasing, there are minimal successes in practice that have addressed these issues, especially within a short time frame. So there is an obvious need for short and medium term approaches that can address the destructive effects of salinity and subsequently complement the long term strategic approaches in salinity management.

In this project, an *in situ* soil remediation technique using electrokinetics is tested, using laboratory experimental models in order to identify the potential of this approach to deal with saline soil more efficiently and effectively.

2 BACKGROUND

2.1 SOME BASIC MINERALOGICAL PROPERTIES OF CLAY SOILS

The physical and chemical characteristics and behaviour of a soil greatly depend on the amount and type of clay minerals present within, since clay particles are chemically and electrically active. Clay particles are plate like in shape, generally smaller than 2µm in lateral dimension and excessively negatively charged. This negative charge on the clay surface is due to the imperfections in the crystal lattice structure (Rae & Parker, 1998) caused by isomorphous substitution, i.e. substitution of one kind of atom for another within the clay mineral structure and the presence of broken bonds. Due to this negative charge, clay particles attract cations from the surrounds. The soil's capacity to attract and hold cations (i.e. the quantity of negative sites on soil surfaces that can retain positively charged ions by

electrostatic forces) is termed the cation exchange capacity (CEC) and reported as $cmol^+/kg$. CEC is generally expressed as the sum of the exchange sites of the most common cations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+).

When the clay minerals are in contact with water, they readily react with the dipolar water molecules and create a thin film of water around the clay mineral containing exchangeable cations, which is referred to as the diffused double layer (DDL). The innermost layer of water (adsorbed water) is strongly held by the surface charge with an outer layer of gradually diffusing electrostatic forces. The electrical potential at the boundary between the inner and outer layers of the DDL is termed as soil's zeta potential (ς), which strongly depends on the ionic concentration of the pore solution.

The charges (valence) of the major cations within this DDL have a great influence on clay behaviour in terms of swelling, dispersion and flocculation. When more Na ions occupy the negative sites on the clay surface relative to other cations, they attract more water molecules from the surround and easily hydrate leading to swelling and subsequent easy dispersion. In contrast, when higher valent cations occupy negative sites on the clay mineral, due to the higher ionic bonding, the ability to hydrate and disperse is lessened and clay particles tend to form 'flocs'.

2.2 CHARACTERISATION OF SALT AFFECTED SOILS

'Salinity' and 'sodicity' are the terms used to describe the effects of soluble salts in soil. Salinity refers to the total concentration of all soluble salts in the soil, which are typically chlorides, sulfates or carbonates of sodium, calcium and magnesium with the most common being sodium chloride (NaCl). Sodicity represents the amount of exchangeable sodium ions (Na^+) in the soil compared to other exchangeable cations, predominantly being calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), hydrogen (H^+) and aluminium (Al^{3+}).

The soluble salts dissociate (electrolyse) in water to cations and anions, creating an electrically conductive media. As a result, saline soils are capable of conducting an electrical current. The higher the concentration of salts in the soil, the higher the current an aqueous solution could carry. The degree of salinity of a soil can therefore be assessed by measuring the electrical conductivity (EC) of the soil. The common parameter used to characterise the degree of salinity is the electrical conductivity (in mS/cm) of a saturated soil extract (EC_e). The electrical conductivity measured using the 1:5 soil water suspension method, $EC_{1:5}$ (which is a more convenient and a quicker method) can be converted to EC_e using established correlations depending on the soil textural classification as proposed by Slavich & Petterson (1993). An EC_e between 8 and 16 is considered highly saline where only salt tolerant plants yield satisfactorily. An EC_e greater than 16 is extremely saline and only a few salt tolerant plants yield satisfactorily.

Saline soils transform into sodic soils when much of the chlorine washes away (occurs when saline groundwater levels fall), leaving behind sodium ions attached to the negatively charged clay particles in the soil. The greater the proportion of sodium in the total exchangeable cations, the more sodic the soil is.

Sodicity is generally measured by ESP (exchangeable sodium percentage) while SAR (sodium absorption ratio) has also been quoted as a good indicator of the degree of sodicity (Halliwell et al., 2001; van de Graaff & Patterson, 2001). ESP is the proportion of exchangeable sodium on the clay surface relative to the total exchangeable cations. SAR is the relative proportion of dissolved sodium in the pore solution compared to the square root of the other dissolved cations; generally calcium and magnesium. The ESP and SAR are related by the Gapon equation (Equation 1), which governs the equilibrium between cations and other counter-ions balancing the negative charge on the clay surface.

$$\frac{Na_c}{Ca_c + Mg_c} = k\frac{[Na]}{\sqrt{[Ca]+[Mg]}} \qquad (1)$$

where Me_c is metal ion on clay surface,
[Me] is metal ion in pore solution and
k is the Gapon exchange coefficient.

Traditionally, an ESP between 6 and 14 is considered to be sodic while an ESP greater than 15 characterise soil as strongly sodic. According to van de Graaff & Patterson (2001) ESP more than 6 is considered sodic. The US salinity laboratory considered ESP greater than 15 to be sodic (Halliwell et al., 2001).

2.3 ELECTROKINETIC SOIL TREATMENT

Electrokinetics is a promising soil treatment technique, in particular in the remediation of contaminated land (Ugaz et al., 1994; West & Stewart, 1995; Pamukcu, 1997; Reddy et al., 2001; Chou et al., 2004). The principles of electrokinetic remediation rely upon the application of a direct current across the soil between two (or more) electrodes. Passing an electric current causes charged species present in the soil solution to migrate towards an oppositely charged

electrode. The transportation of charged species across the soil involve several mechanisms such as electroosmosis (migration of water through the capillary network of soil particles under the influence of an electric field), electromigration (transport of charged chemical species under an electrical gradient) and electrophoresis (movement of charged particles under an electric field).

The review of data from somewhat similar studies conducted in the USA and Iran reveals that design of electrokinetic treatment processes are often case specific, requiring a trial and error approach. The main design parameters to be considered include an estimation of the required current density, voltage gradient, type and placement of electrodes and sources for power supply. In some situations, soil conditioning and enhancement techniques need to be employed to enhance the electrokinetic movement of species through the soil. The selection of appropriate materials, methods and subsequent estimation of required durations of treatment are dependent on many factors that include the type and characteristics of the soil to be treated, concentration and characteristics of contaminants, required degree of treatment, environmental and climatic conditions and the potential end use of the treated soil.

3 MATERIALS AND METHOD

3.1 EXPERIMENTAL SOIL

Laboratory investigations were performed on saline soil samples collected from farmland located at Mt. Mercer, an area identified as significantly affected by soil salinity, in the Ballarat region, in central Victoria. This soil is classified as inorganic silt (ML) according to the unified soil classification system. According to the textural soil classification, this soil falls in the category of silty loam.

The original physical, mineralogical and chemical properties of this soil were initially evaluated and were used as the datum for comparison of the results with the effect of electrokinetic processing. The original properties of the test soil are summarised in Table 1.

Table 1: Original properties of experimental soil.

Characteristic	**Data**
$EC_{1:5}$ (Electrical Conductivity) (mS/cm)	2
EC_e (Electrical Conductivity) (mS/cm)	18
pH	4.5
Pore fluid cationic concentration (mg/kg)	
Na	230
K	8
Ca	18
Mg	80
Cationic concentration on clay surface (mg/kg)	
Na	430
K	47
Ca	110
Mg	240
CEC (at pH 7)	5.5
ESP (Exchangeable Sodium Percentage)	34
SAR (Sodium Absorption Ratio)	8
Consistency Limits (%)	
LL (Liquid Limit)	30
PL (Plastic Limit)	23
PI (Plasticity Index)	7
Unconfined Compressive strength (kN/m^2)	38

3.2 EXPERIMENTAL PROCEDURE

In this project, the experiments were conducted on laboratory scale models. These models were constructed in glass tanks by placing a 12 cm thick layer of contaminated soil (saline soil) to represent field density of 1500 kg/m^3 at the field moisture content of 25%. The tanks were fabricated using glass mainly due to glass being relatively chemically and electrically neutral (minimise reactions with contaminated soils). Separate tanks were set for each planned electrokinetic treatment period of 14 days, 30 days, 45 days and 60 days.

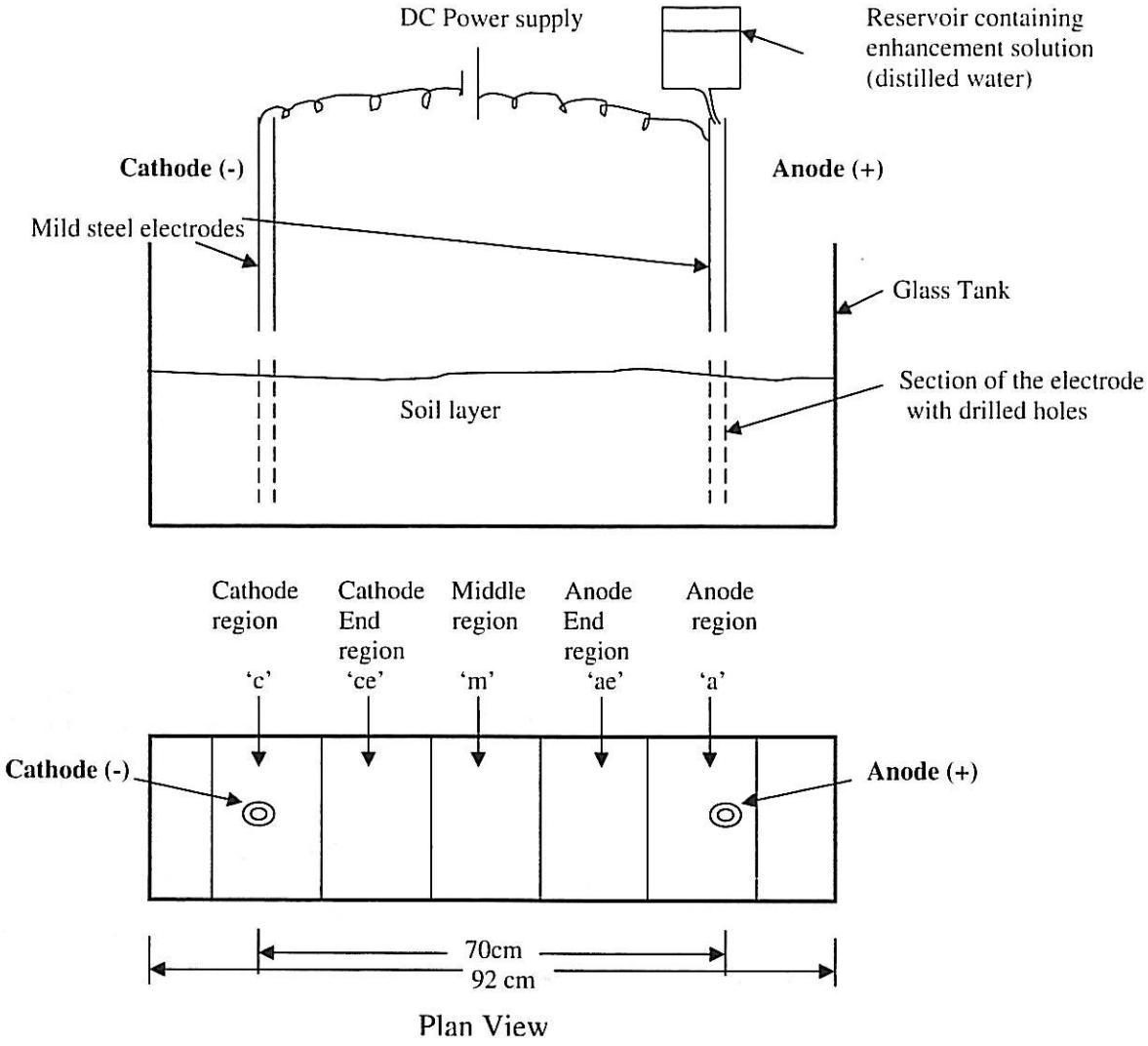

Figure 1: Schematic of the laboratory set up for electrokinetic treatment of saline soil.

Two mild steel tubes (25mm diameter, hollow, with holes drilled through the walls of the tube to allow the liquids to move freely) were placed at both ends of the tank to serve as electrodes. Soil samples were continuously supplied with distilled water, via the hollow core anode from a reservoir (Figure 1), in order to enhance the electrokinetic processes, particularly the electroosmotic flow. The reservoirs were kept filled at all times so that there is a continuous automatic flow of water through the anode to the soil.

Mild steel electrodes were chosen because they are readily available at a low cost, easy to fabricate and have considerable strength. Although more inert electrodes such as graphite may be better, some preliminary experiments indicated that the effects of iron corrosion at the anode do not significantly affect the performance of the system in moving water or the major cations through the soil.

These soil samples were subjected to a direct current (d.c.) with a constant voltage of 35 volts to provide a voltage gradient of approximately 0.5 V/cm. Similar research reported in the literature indicates the use of a range of voltage gradients (e.g. 3 V/cm (Pamukcu et al., 1997); 0.07 V/cm to 0.53 V/cm (Sadrekarimi & Sadrekarimi, 2003) to move salt across soil with various degrees of success. The voltage gradient for these experiments was selected considering the results of some previous, preliminary experiments conducted in the electro-geo laboratory of the University of Ballarat.

After the required electrokinetic processing period, soils at different regions across the soil cross section were analysed for their chemical and physical properties. These regions were designated as;

'anode', 15-20 cm section around the anode electrode,
'anode end', 15-20 cm section between anode region and the middle,
'middle', 15 –20 cm section in the middle,

'cathode end', 15-20cm section between middle region and cathode region and 'cathode', 15-20 cm region around the cathode (Figure 1).

3.3 EXPERIMENTAL METHODS

The Unconfined Compression (UC) tests were performed using the Instron Universal Testing Machine. The original soil was prepared for this test by compacting soil in a 35 mm sampler tube at *in situ* water content (25%) to arrive at *in situ* density of 1500 kg/m^3. After the soil is electrokinetically treated, 35 mm core samples were extracted from the soil in the tank by pushing a thin walled 35mm sampler with a cutting edge into the soil.

All other tests on electrokinetically treated soil were conducted on representative specimens prepared after drying and homogeneously mixing the entire soil volume in each region.

Electrical conductivity ($EC_{1:5}$) and pH were analysed using the 1:5 soil: water suspension method (Slavich & Petterson, 1993).

Ionic concentrations of Na, Ca and K, were estimated using flame photo spectrometry and Mg using atomic absorption spectrometry. The cation exchange capacity (CEC) was estimated using the ammonium acetate CEC analysis technique at pH 7.0. The CEC experiments were conducted by Incitec Pivot Limited at Werribee, Victoria. The exchangeable sodium percentage (ESP) and Sodium Absorption Ratio (SAR) was computed using the Gapon equation (Equation 1).

The consistency limits experiments (Liquid Limit LL and Plastic Limit PL) were conducted using the method described in Australian Standard (AS 1289.3.1.1-1995). Distilled water was used as the mixing liquid for all experiments.

4 RESULTS AND DISCUSSION

Within days, organic matter (observed as a damp brown/ black colourisation) and various other chemical species (observed as salt accumulation at the cathode electrode) moved across the tank towards the cathode (Figure 2). The salts accumulated around the cathode were found to be predominantly hydrated sodium carbonates.

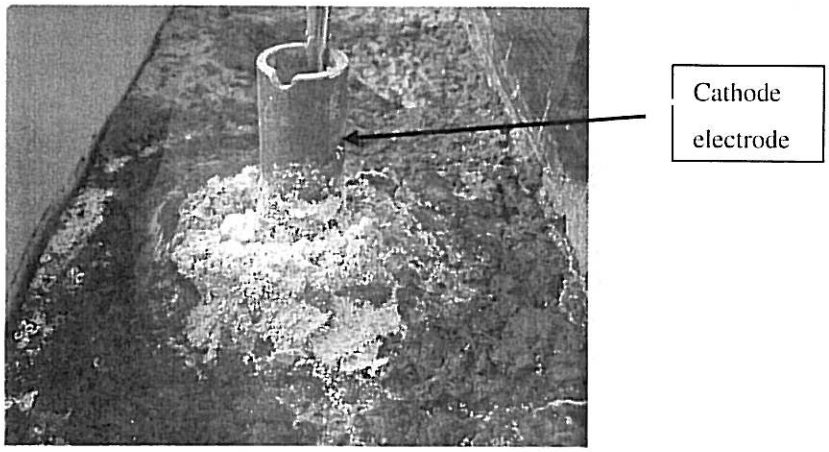

Figure 2: Accumulation of materials including salts around the cathode region.

After 10 to 14 days, an area towards the cathode end of the soil layer started drying, (see Figure 3), developing a zone of low electrical conductivity. This area corresponded to the lowest electrical conductivity reported during the experiments. With the increase of electrokinetic processing time, cracks developed in the soil layer with the most prominent cracks between the sections of variable moisture conditions (dry and wet) across the soil surface.

With time, the flow of current through the soil layer started to decrease. As can be seen from Figure 4, the amperage of approximately 200 mA, recorded at the initiation of the experiment, dropped significantly to a level of less than 10 mA, in about 14 days.

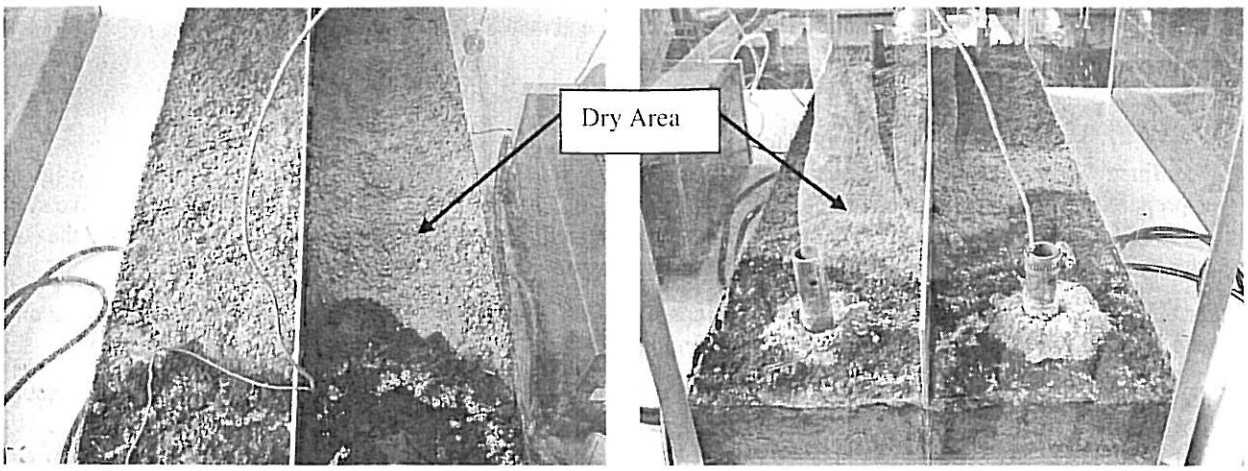

Figure 3: Development of a dry area towards the cathode region.

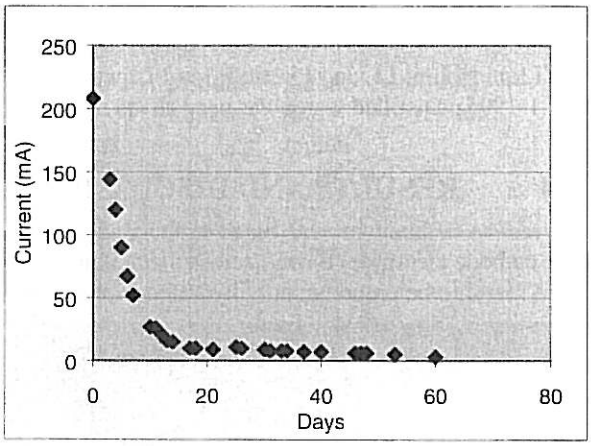

Figure 4: Variation of current flow across the tank with time.

4.1 VARIATION OF PH

Figure 5 shows the variation of pH across the tank, with time. It is noticed that a pH gradient is generated across the tank creating an acid front at the anode and a base front at the cathode. The development of this pH gradient is due to the process of electrolysis; i.e. the chemical reactions associated with the electric field. When a direct current is applied, water in the immediate vicinity of the electrodes is electrolysed and oxidation occurs at the anode, generating an acid front while reduction takes place at the cathode producing a base front. These electrolysis reactions are,

$2H_2O - 2e^- \Rightarrow O_2\uparrow + 4\,H^+$ $\quad E_0 = -1.229$ anode

$2H_2O + 2e^- \Rightarrow H_2\uparrow + 2\,OH^-$ $\quad E_0 = -0.828$ cathode

where E_0 is the standard reduction electrochemical potential, which is a measure of the tendency of the reactants in their standard states to proceed to products in their standard states.

These electrolysis reactions cause the pH to decrease at the anode and increase at the cathode. Development of this pH gradient (acid/ base profile) and its effects on the species transport through clay medium have been discussed in detail and well documented by many researchers (e.g. Acar et al., 1990; Pamukcu & Wittle, 1992; Acar & Alshawabkeh, 1993; Eykholt & Daniel, 1994; Jayasekera, 2004, etc). In conclusion, it has been shown that the pH gradient developed across the porous medium affects the flow, flow efficiency and the extent of ion migration whilst it can also have significant effects on other complex electrokinetic processes.

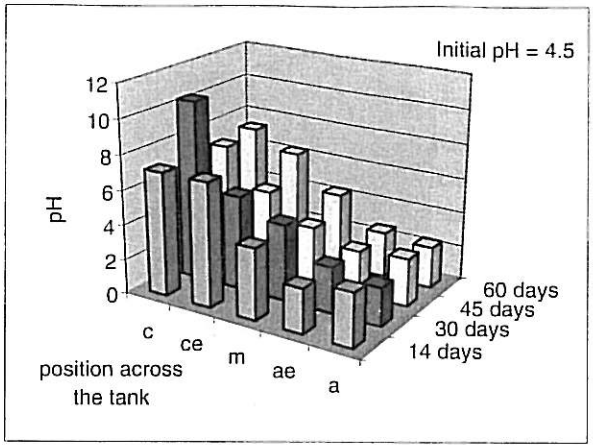

Figure 5: Variation of pH across the soil with time.

From the results, it is noticed that acid front is migrating across the soil, towards the cathode, with time. This migration of acid front can be due to the combined effect of,

(i) advection under the hydraulic potential difference,
(ii) advection due to electroosmosis,
(iii) diffusion due to concentration gradients and
(iv) migration under an electrical gradient.

In 14 days, the pH recorded at the middle of the tank is about 4, which indicates that the acid front has reached the middle of the tank. This has further advanced towards the cathode in 45 days as noted by the pH recorded (pH 4) in this region in 45 days. The development of this pH gradient reached a peak in 30 days, before the acid front reached the cathode, with pH 2 at the anode and 10 at the cathode. With increasing processing time, beyond 30 days, the pH gradient across the tank appeared to stabilise around pH 2 at the anode and pH 7 at the cathode. The base front is retarded from moving towards the anode by the electroosmotic flow and by precipitation of metal hydroxides. The current has declined significantly as the soil has increased resistance to current flow in that direction.

With time, chemical reactions associated with the electric field slow down. This is due to several reasons that may include a decrease in water molecules available for electrolysis, redistribution of ions across the soil layer and a gradual decline of the current flow. The variation of pH within the system is retarded by the buffering capacity of the soil. The cation exchange capacity (CEC) of the soil minerals and the availability of organic species and the salts (such as $CaCO_3$) that could react with the acid front increase the buffering capacity of the soil. As a differential in soil zeta potential develops (associated with the changes in soil pH and also the changes in the chemical concentrations in the pore solution), a change in the electroosmotic potential occurs across the tank. With a higher pH, the zeta potential is more negative and the electroosmotic flow in this zone becomes greater, causing it to dry out and shrink relative to the zones of lower pH and more positive zeta potential.

4.2 VARIATION OF ELECTRICAL CONDUCTIVITY

The variation of electrical conductivity ($EC_{1:5}$), across the tank with time is presented in Figure 6. In general, it is observed that high EC values are recorded in the regions of the anode, anode end and cathode. The high EC values recorded at the anode are due to the generation of hydrogen ions that are very conductive (mobile) in solution. Moderately high EC values observed in the anode end indicate that the acid front is travelling across this region, gradually reaching the middle of the tank. The high EC values recorded at the cathode are due to the accumulation of cations (predominantly Na^+ ions) in this area. At day 30, when the pH reached 10, the hydroxyl ions produced from electrolysis at the cathode may also be contributing to higher EC values in this zone. The high EC values from the cathode region are confined to the zone immediately around the cathode because the base front does not migrate out towards the anode to any significant extent.

The lowest EC recorded throughout the experimental duration corresponds to an excessively dry area that developed at the cathode end after about 14 to 30 days. This dry area was initially observed originating around the middle of the tank and then gradually confined in the region of the cathode end.

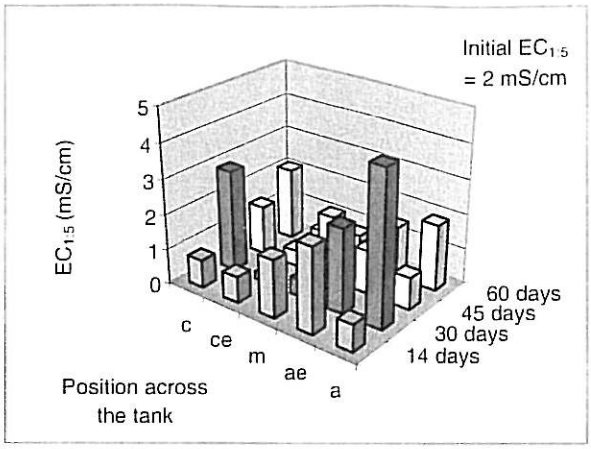

Figure 6: Variation of Electrical Conductivity ($EC_{1:5}$) across the soil with time.

4.3 VARIATION OF SOIL MOISTURE CONDITIONS AND ELECTROOSMOTIC FLOW

In these experiments there was a continuous supply of distilled water from the anode. Up to about 14 days, an appreciable amount of electroosmotic flow occurred which kept the whole soil profile reasonably moist. The migration of water during this period is due to a coupled hydraulic and electric gradient. However, the electroosmotic flow started to diminish gradually along with a decrease in current flow. The increased amount of exchangeable cations in the soil solution (in the pore water) would also have contributed to the decrease in electroosmotic flow due to the suppression of the DDL. However, the ingress of water from the anode end managed to keep the anode region comparatively wet. This would also have been facilitated by the hydraulic head at the anode.

As differential in soil zeta potential develops (associated with the changes in soil pH and also the changes in the chemical concentrations in the pore solution) a change in the electroosmotic potential occurs across the tank and certain areas in the tank dry out relative to other areas. These areas have a low conductivity and are depleted of the major cations.

Observations made by Ugaz et al., (1994) indicate that low permeable soils subjected to electrokinetic processing are prone to develop suction pressures, thus initiating a consolidation process. They found this to be more pronounced in the anode region, even with the ingress of water through an anode compartment. They reasoned that the development of such suction pressures are due to the insufficient supply of pore fluid from the anode and subsequent slow migration of water from anode to cathode as a result of the low permeability of the soil.

However, in our experiments the greatest suction pressures occurred in the cathode end, leading to cracks developing between the dry and wet zones. This was due to the differential in electroosmotic flow rates across the soil profile. At a pH of 2 the zeta potential will be close to zero or could even be positive. This would reduce the electroosmotic flow towards the cathode or even reverse it. The anode end would therefore remain moist due to the small hydraulic head whilst the cathode end tends to dry out. The dry zone having a low EC is where the largest voltage drops occur across the soil profile. The voltage gradient across the anode and anode end regions declines as the processing time increases. This will also lead to a decreased electoosmotic flow through these regions compared to the dry zone where the voltage gradient is much larger.

4.4 MIGRATION OF SODIUM (NA) IONS AND EFFECTS ON ESP AND SAR

Figure 7 presents the migration of Na ions in the pore solution, across the tank with time. The variation of Na ion concentration on the clay surface is given in Figure 8. It is noted that a majority of Na ions have migrated towards the cathode. These Na ions moved relatively easily and quickly with the majority of Na ions having migrated from anode towards the cathode within the first 14 days. A corresponding variation is noted with Na ion content on the clay surfaces (Figure 8).

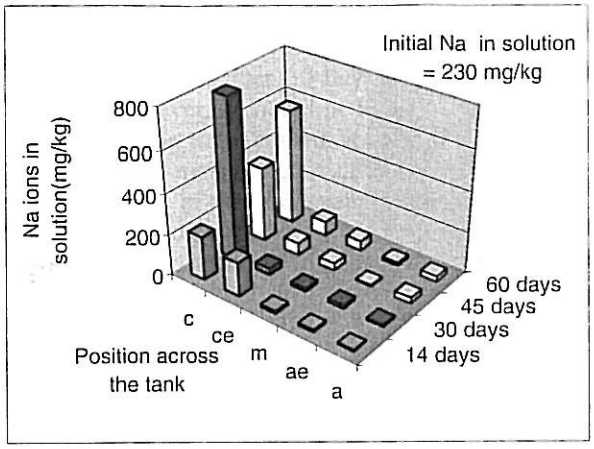

Figure 7: Variation Na ion concentration in pore solution with time.

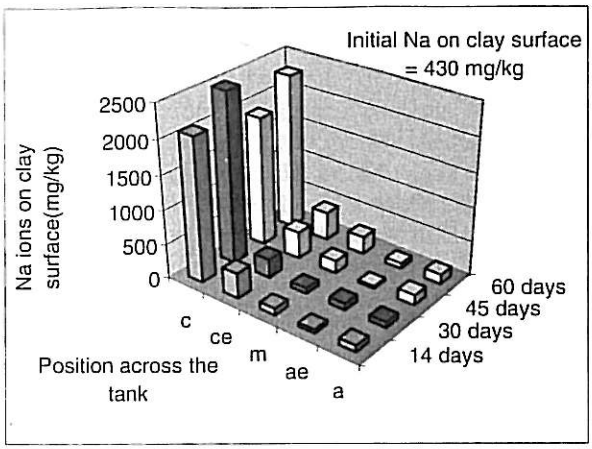

Figure 8: Variation of Na ion concentration on clay surface with time.

The ESP and SAR are presented in Figure 9 and Figure 10 respectively. It can be observed that both ESP and SAR have decreased significantly across the soil except in the cathode region where most of the mobile cationic species are deposited and accumulated.

The ESP in the regions of anode, anode end and middle and the cathode end of the tank is generally less than 6 while SAR is lower than 3. According to classifications proposed to assess the degree of sodicity using ESP and SAR, the soil in the anode, anode end, middle and the cathode end of the tank can now be classified as having a very low to negligible sodicity.

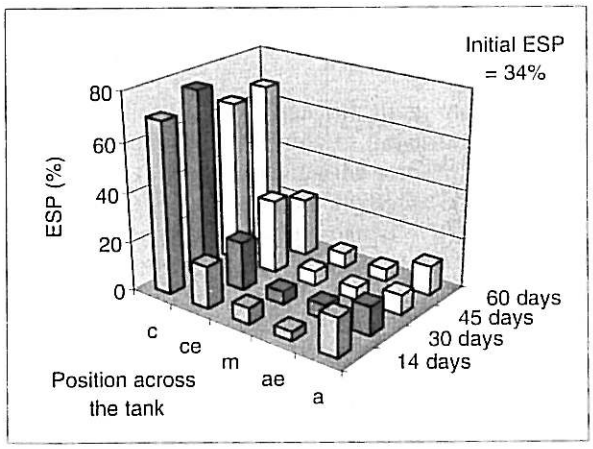

Figure 9: Variation of ESP with time.

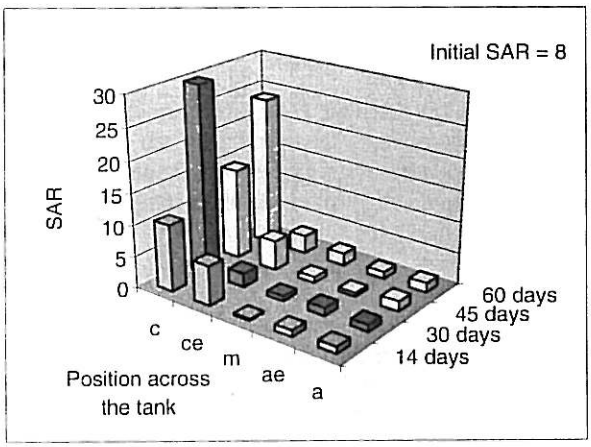

Figure 10: Variation of SAR with time.

A fair correlation ($R^2 = 0.76$) was observed between ESP and SAR as presented in Figure 11. This observation reiterates the relationship between ESP and SAR and also suggests the applicability of Gapon equation for the experimental soil. The Gapon exchange coefficient (k) for this soil is estimated to be 0.225.

4.5 MIGRATION OF OTHER CATIONS (MG, CA AND K) AND VARIATION IN CEC

The monovalent K ions showed a similar migration trend to Na ions. The divalent cations of Mg and Ca appear to be less mobile than the monovalent cations.

Although the current dropped well below 10 mA in about 14 days, ion migration, particularly Na ion movement and to some extent K ion movement continued for a considerably longer time period. The movement of ionic species across the soil profile is less influenced by electroosmosis as the process time increases. Electromigration then becomes the predominant transport mechanism.

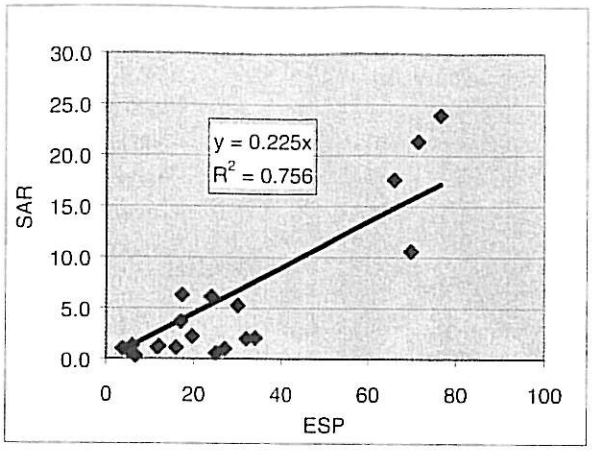

Figure 11: Relationship between ESP and SAR.

The cation exchange capacity (CEC) of the original (untreated) soil is 5.5. After the electrokinetic processing, the CEC at the anode region has reduced to less than 2. In the middle of the tank, the CEC was around 6, which is closer to the original CEC. At the cathode region, the CEC has increased to around 14 (more than doubled the initial CEC).

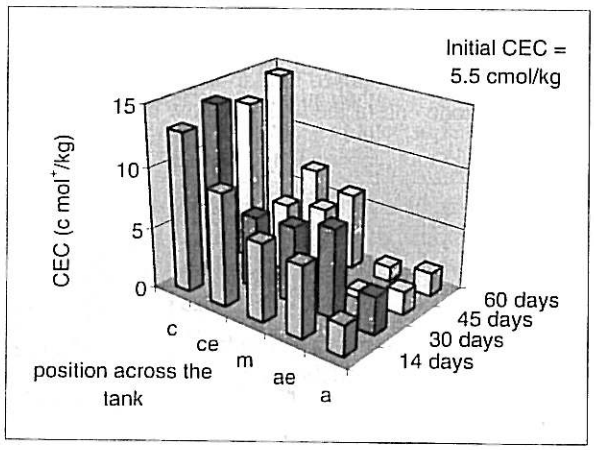

Figure 12: Variation of CEC with time.

The variation of CEC in this manner may be related to the pH gradient across the tank (see Figure 13). Towards the anode, the pH is low. This indicates that there is a reduction in the negative charge on the soil surface. As a result, the CEC of the soil reduces. Towards the cathode, the pH is high and thus the negative charges on the soil particles are high. These soils therefore show a higher CEC. The migration and accumulation of organic matter towards the cathode region may also have contributed to this high CEC at the cathode region, as organic matter also possesses high CECs.

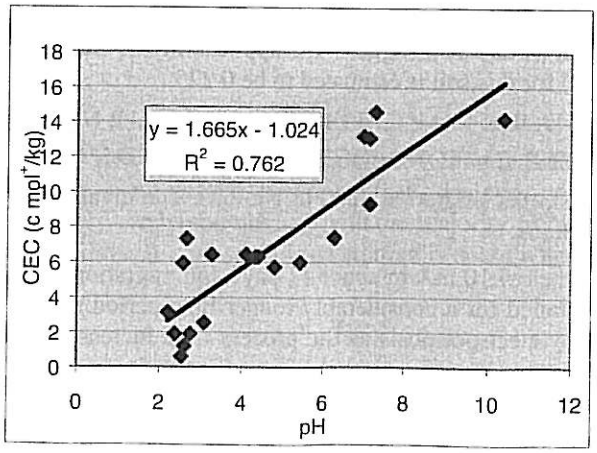

Figure 13: Relationship between pH and CEC.

4.6 VARIATION OF STRESS STRAIN CHARACTERISTICS

As can be seen from the stress strain graphs (Figure 14), there is an increase in the peak strength both at the anode end and the cathode end after 30 days of electrokinetic processing. Also, it is noted that the soil shows more brittle behaviour. However, it should be noted here that there are significant variations of moisture contents across the soil. After 30 days, the water content at the cathode end region was 4% while at the anode end the water content was 12%. This decrease in moisture content and dry nature of soil would have contributed to the brittle nature as well as the apparent increase in the peak strength at the cathode end. The increase in peak strength in the anode end region could have been affected by the possible iron ion intrusion due to the corrosion of the mild steel electrode in the anode region. These consequences would have concealed the effects of electrokinetics alone on these soil properties.

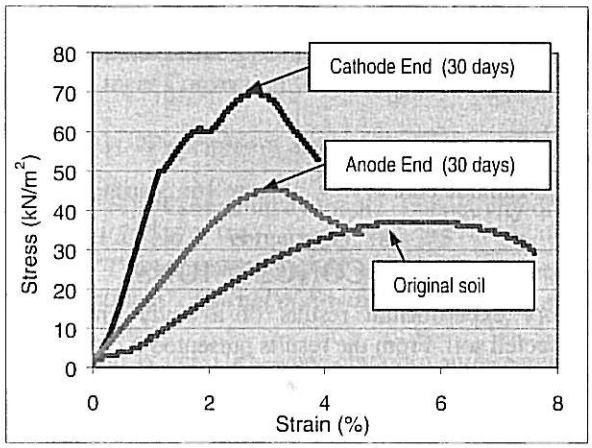

Figure 14: Variation of stress strain characteristics with time.

Beyond 30 days, no core specimens could be retrieved for strength tests from cathode end area due to the excessively dry nature of soil.

Exact identification and quantification of the electrokinetic effects on strength characteristics demand further investigation and quantification of the effects of iron ion intrusion on the soil. The strength characteristics should be evaluated on specimens having the same water content (after electrokinetic processing and compacting at a constant water content) in an attempt to study the effects of electrokinetic processing alone on strength characteristics. These investigations are currently in progress.

4.7 VARIATION OF PLASTICITY CHARACTERISTICS

The effects of electrokinetic processing on plasticity characteristics were evaluated using consistency limits. Consistency limits provide an important indication of the hydraulic performance of a clay soil (Benson et al., 1994), particularly in terms of the water absorption capacity from semi solid to plastic state and plastic to liquid state. The plasticity properties of a soil depend on the soil water content and also on the variations in the chemistry of the pore solution.

The experimental soil used in this investigation does not contain a high clay fraction and is classified as a low to medium plastic silt (ML). As such, the soil is not very responsive to consistency limits test. The slight variations in the liquid limit (LL) and plastic limit (PL) are not significant enough to draw any definitive conclusions. However, the slight gradual increase in the LL and PL in the cathode end with time (Figure 15) indicates the higher surface negativity of soil in this region. The higher surface negativity of the soil is due to ionic redistributions with consequent increases in the pH (Figure 5) and CEC (Figure 12) thus increasing the water sorption ability of the soil. If a soil mineral has a greater ability to attract water to its surface, it can absorb more water before reaching the LL. The majority of sodium ions that have travelled towards the cathode end region can also affect this increase in the LL and PL. More Na ions in the pore solution and on the particle surface increase the water sorption behaviour of the soil since Na ions can attract more water.

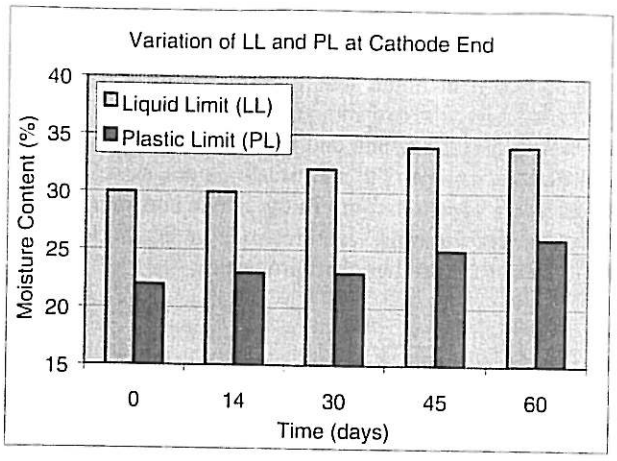

Figure 15: Variation of LL and PL at cathode end.

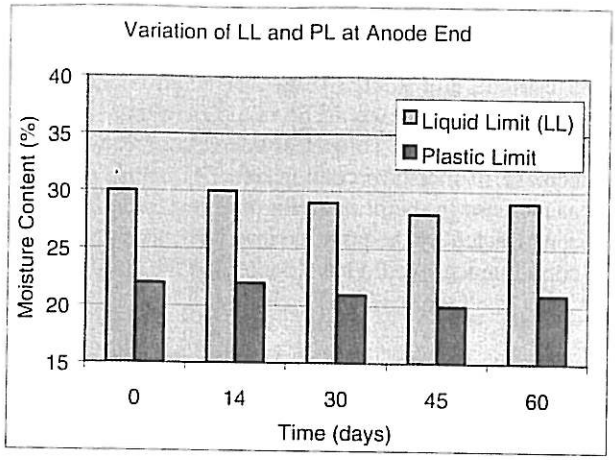

Figure 16: Variation of LL and PL at anode end.

5 CONCLUSIONS

This paper has presented laboratory experimental results of a study undertaken to investigate the effects of electrokinetic treatments on a salt affected soil. From the results presented it can be concluded that:

(i) With the application of a direct electric current to the soil-liquid medium, the water particles at the anode and cathode hydrolysed and generated an acidic medium at the anode and an alkaline medium at the cathode. The acid front (H^+) advanced towards the cathode and the alkali front (OH^- ions) migrated towards the anode. These reactions changed the ionic concentration of the pore fluid, and the pH of the soil. After about 30 days of electrokinetic processing, the pH gradient across the soil stabilised.

(ii) With time, the ionic concentration of the pore fluid gradually reduced across most of the soil layer. When the ionic concentration is depleted the resistance to current flow is increased. As a result, the current flow across the soil gradually decreased, and so did the electroosmotic flow. Excess salt (ions in solution) in the pore water could also have caused a decrease in electroosmotic flow due to the suppression of the DDL. Across the soil layer, the moisture content started to vary and regions were developed with different moisture contents with the driest area being the cathode end region. This is predominantly due to the diminishing electroosmotic flow from anode to cathode. The suction pressures developed in the drying areas resulted in some shrinkage and subsequent development of cracks between different moisture regions.

(iii) The highest electrical conductivity values were observed at anode, anode end and cathode. The high EC values recorded at the anode are due to the generation of hydrogen ions that are more mobile in solution compared to other ions. Somewhat high EC values observed in the anode end indicate that this acid front travelled across this region. The high EC values recorded at the cathode are due to the hydroxyl ions produced at the cathode and accumulation of cations, particularly Na ions in this area. These high EC values are almost confined to the cathode region since the alkaline front is not as mobile as the acid front. The lowest EC corresponds to the driest area (cathode end) across the tank.

(iv) A majority of Na ions moved relatively easily and quickly from anode to cathode and with time accumulated around the cathode region. Consequently, the ESP and SAR decreased significantly in the other regions across the soil. As a result, the degree of sodicity decreased to a negligible level.

(v) Due to the change in the ionic composition in the porous medium and subsequent effects on the double layer ionic concentration, CEC and pH, the water adsorption and thus the consistency characteristics of the soil changed. The liquid limit (LL) and plastic limit (PL) increased at the cathode due to the accumulation of Na ions in this region.

(vi) The compressive strength of the soil appeared to increase both at the anode end and cathode end. However this apparent increase is also attributed to the variation of moisture content and possible intrusion of iron ions from the oxidation of the anode electrode. Thus, further investigations are needed to quantify the effects of electrokinetic processes alone on the strength properties of the soil.

6 ACKNOWLEDGEMENTS

The results presented in this paper are part of an on going project carried out at the School of Science and Engineering of the University of Ballarat. The first author is supported by the University of Ballarat's research starter funding scheme and Australian postgraduate award (APA). The authors thankfully acknowledge Mr. Paul Brass for technical assistance, Mr. Graeme Hood for support and cooperation in supplying electrical devices and advice in some technical matters, Dr. Brian Chappell for his innovative ideas and assistance with practical and analytical work.

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